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A GIS-based method for modeling urban-climate parameters using automated recognition of shadows cast by buildings

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ABSTRACT

Projections for the next thirty years predict a rapid growth in urban population, particularly in the less developed regions. Constructing and updating GIS databases of 3D urban form is essential for analyzing spatial phenomena related to urbanization. One of these phenomena, urban climate, is influenced by urban morphology. A prerequisite for representing urban morphology is 3D data including the height of urban features. In cases where no city plans or field survey data are available, a viable option is to use remotely-sensed data for recognition of urban features. Often, the output of automated object recognition consists of footprints of urban features. A known method for calculating a feature's height for reconstructing 3D urban morphology is to use the shadows cast by those features.

A GIS-based method for constructing 3D geodatabases of urban morphology from cast shadows and analyzing geometrical parameters for urban-climate analysis was developed. The method focuses on the aspect-ratio of inner courtyards and its relation to solar access. A case-study is presented to demonstrate the feasibility of this method. Results demonstrate that the method offers a reliable and low-cost process for constructing 3D geodatabases that can be applied to the analysis of urban-climate parameters in less developed regions, where costly data and sophisticated processing practices are less accessible. This method can enhance the understanding of microclimatic conditions and facilitate climate conscious and sustainable future urban planning in sprawling urban centers.

1. Introduction

The last decade has witnessed a turn-over in the urban-rural ratio and today more than half of the world's population lives in urban environments. Projections for the years 2020–2050 predict further growth in urban population, primarily in the less developed regions which will account for most of this growth (United Nations Department of Economic Affairs, 2010). Invariably, various urban phenomena such as urban climate, urban pollution, urban sprawl and urban runoff are influenced by the process of urbanization (Cui & Shi, 2012; Grimmond, 2007; Miller et al., 2014; Qiao, Tian, & Xiao, 2013; Targhi & Van Dessel, 2015). The analysis of such phenomena and the representation and integration of the urban structure in different numerical models relies greatly on the existence of updated geodatabases of 3D urban form. Geodatabases are a specific type of databases which can manage, process and analyze spatial data within their data model. A geodatabase can represent simple and complex geometrical objects and their spatial relations and is often managed within a Geographical Information Systems (GIS) (Güting, 1994; Breunig & Zlatanova, 2011; Yeung & Hall, 2007).

Geodatabases and particularly GIS-based geodatabases of urban form have developed rapidly in recent years and have become a common practice particularly in the more developed regions. National mapping agencies and, on a local scale, city municipalities and regional councils, have manage to develop sophisticated national and local GIS geodatabases to maintain and update the representation of urban features. These geodatabases are used to support research and spatial analysis of urban phenomena, infrastructure management, urban planning, disaster management, visualization and decision-making (Breunig & Zlatanova, 2011; Gröger & Plümer, 2012). Sophisticated mapping technologies, such as laser scanning, solid modeling and remotely-sensed imagery are used for reconstructing buildings and other urban features in 3D (Heo et al., 2013; Sahin et al., 2012; Tong et al., 2012). These technologies are based on acquiring costly data, sophisticated processing applications and on training highly-skilled analysts. In less developed regions such geodatabases often do not exist due to lack of funds and limited surveying practices. As a result, development of GIS geodatabases as well as the integration of 3D models of urban form is lagging behind (El Garouani, Alobeid, & El Garouani, 2014). These databases include often only building footprints with no height information, or at best localized 3D models which focus mainly on historical and cultural heritage sites (Tack, Buyuksalih, & Goossens, 2012).

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The development of 3D urban models is especially important for less developed regions where urbanization processes are dynamic and most pronounced and will continue to accelerate in a dramatic pace (Fig. 1). This stresses even more the need to monitor and understand microclimatic conditions within urban centers in less developed regions.

Comprehensive urban-climate analysis relies greatly on 3D models of urban form. Obtaining the height of buildings is a pre-requisite for deriving urban form parameters, which are commonly used for quantitatively characterizing urban field sites (Krüger, Minella, & Rasia, 2011; Stewart & Oke, 2009). One of these parameters is the aspect ratio (height-to-width or H/W ratio), which is calculated as the ratio between the mean building height and the distance between buildings (width of the street).

A feasible option for addressing the lack of updated city plans and survey data is to employ methods for automated recognition of urban objects, such as buildings, road networks and urban vegetation from remotely-sensed data (Adeline, Chen, Briottet, Pang, & Paparoditis, 2013; Bong, Lai, & Joseph, 2009; Ok, 2013; Manno-Kovacs & Sziranyi, 2015). The high temporal and spatial resolution of space- and airborne data offers an up-to-date representation of the urban environment. Once objects are recognized, classified and vectorized they can be integrated into a GIS geodatabase as urban geometrical features. These geodatabases can be used to extract different geometrical characteristics for modeling and analysis of the urban surface. If further ancillary data such as field surveying and manual digitizing becomes available at a later stage the dataset can be updated and extended as needed. A major concern in automated recognition of urban objects from 2D images is that, vertical (not oblique) remotely-sensed imagery includes only 2D footprints of urban features with no height data (no visible façades). One solution for addressing this problem is to use the shadows that are cast by objects. Extraction of height information based on cast shadows is considered a well-established method for extracting buildings height from a 2D image (Adeline et al., 2013; Al-Najdawi, Bez, Singhai, & Edirisinghe, 2012; Cheng & Thiel, 1995; Tong et al., 2013).

The following presents a method aimed to support the systematic analysis of urban climate in less developed regions. The method, developed in GIS, uses the length of shadows cast by buildings to reconstruct a 3D geodatabase of urban morphology. The study focuses on courtyard houses in hot-arid regions and on evaluating the extent of solar access to these courtyards by extracting and analyzing the H/W ratio parameter in relation to a developed solar access criterion.

2. Materials and methods

2.1. Modeling solar access in urban open spaces

One of the major influences on urban-climate is urban form, i.e. the geometrical attributes of urban features and their arrangement in the urban space (Arnfield, 2003; Grimmond, 2007; Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Oke, 1981; Oke, Johnson, Steyn, & Watson, 1991; Targhi & Van Dessel, 2015). Studies, such as Berkovic, Yezioro, and Bitan (2012); Etzion (1990); Ghaffarianhoseini, Berardi, and Ghaffarianhoseini (2015); Meir, Pearlmutter, and Etzion (1995); Muhaisen and Gadi (2006); Roaf (1990) and Thapar and Yannas (2008) have focused on the climatic performance of open spaces and in particular that of inner courtyards. Courtyard houses are a common building typology in developing countries of hot-arid regions and inner courtyards are considered as thermal moderators in extreme climatic conditions (Abdulkareem, 2016; Golany, 1996; Meir et al., 1995; Ratti, Raydan, & Steemers, 2003; Talib, 1984). These studies have demonstrated that certain morphological characteristics, primarily the geometry and orientation of open spaces, influence microclimatic conditions more than others as these determine the extent of exposure to solar radiation. Solar radiation has been considered as one of the most important aspects in climatic responsive planning and design, especially since mean radiant temperature has a significant effect on the thermal comfort of human beings, particularly in hot-arid lands where summer shading and winter heating through climatic responsive planning is essential. Solar access is defined as the proportion of the area of a building façade or of an open space, which is exposed to the sun during a defined period of time in the heating period, or shaded in the hot periods of the year. It is represented by both the geometry and the orientation of a building or of an open space and therefore acts as an indicator for climatic responsive urban planning. One method for evaluating the extent of solar access is by examining the H/W ratio. The relationship between the H/W ratio and solar exposure can be used to evaluate the extent of climatic responsive urban planning and architectural design. To model solar access the position of the sun, represented through the solar azimuth (AZI) and altitude (ALT) angles, is required in addition to the H/W ratio. AZI is defined as the horizontal direction of the sun from the true north – measured clockwise, as illustrated in Fig. 2. ALT represents the angle of incidence between the sun and a horizontal plane, as illustrated in Fig. 3. Computation of AZI and ALT is based on well-known

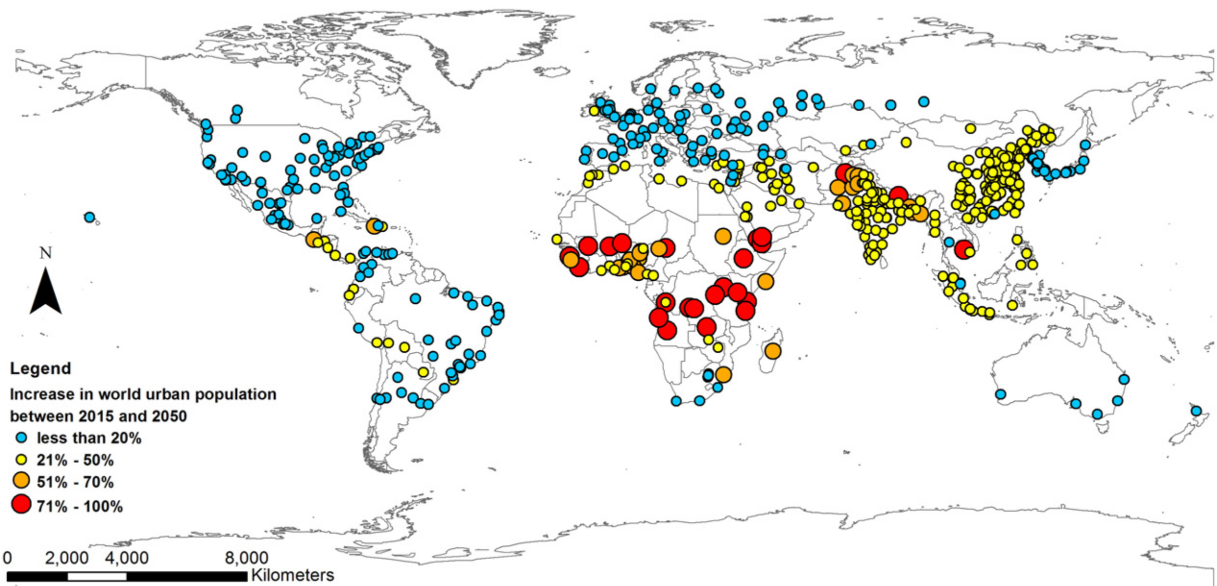

Fig. 1. Increase in world urban population (in %) between the years 2015–2050 in major urban centers. Calculations are based on data retrieved from the World Urbanization Prospects, Unite Nations, Department of Economic and Social Affairs (http://esa.un.org/unpd/wup/).